where a sudden outburst of heat can be provided at a definite moment in order to produce the control curve—a condition difficult to satisfy when employing a non-conducting substance like rubber. In all cases, however, where such a "control" curve can be made, and where the motion of the galvanometer can be assumed to be governed by linear differential equations with constant coefficients, the method may be employed; it is not limited necessarily to the case of galvanometer deflections produced in response to changes of temperature in a thermopile.

On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese.

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Section 1.—*Aim of the Research.*

Since its discovery by one of us in 1883, the material now universally known as manganese steel, that is the iron-manganese alloy containing about 12 to 14 per cent. manganese and 1·10 to 1·25 per cent. carbon has, on account of its many remarkable properties, been the subject of many researches.

2. The investigation of its magnetic behaviour in connection with thermal and mechanical treatment has taken a prominent place among them, as this method of investigation, perhaps more than any other, promised to give an insight into the constitution of steel alloys, and accordingly to show how their properties might be influenced in any desired direction. Manganese steel has not only been important in itself, but by reason of the light it has thrown upon the laws relating generally to steel alloys.

3. Manganese steel as cast or forged is non-magnetic and when this steel is treated in the ordinary way to obtain its peculiarly high toughness and tenacity, that is, after being heated to 1000° C. and quenched in water, it is only very slightly magnetic, namely, equivalent to less than one part in a thousand as compared with Swedish charcoal iron. It can, however, be made to reach a specific magnetism about two-thirds of that of pure iron by prolonged heating at 520° C. Cooling down to the temperature of liquid

air (−182° C.) had practically no effect on this steel provided it was either in the non-magnetic or strongly magnetic condition, but the magnetism increased, if it was in an intermediate condition before immersion.

4. Now the non-magnetic condition of manganese steel has been considered as analogous to that of some nickel-iron alloys. As is well known, some of these latter alloys may be non-magnetic at ordinary temperature, but can be rendered magnetic at the same temperature, by cooling them to a sufficiently low temperature and allowing them to return to normal temperature. It was suggested therefore, that possibly the temperature to which manganese steel must be cooled down in order to become magnetic, might be still lower than that of liquid air. Although this view was probably not correct, as pointed out by one of us, it was thought to be interesting to cool the manganese steel down to the temperature of liquid hydrogen (−253° C.) or even further to that of liquid helium (−269° C.) to ascertain whether, starting with the material in its non-magnetic condition, it could be made magnetic at ordinary temperatures.

5. A preliminary experiment at liquid hydrogen temperature showed that this change, as expected by some, did not occur. The question, however, remained for other non-magnetic manganese-iron alloys, containing varying percentages of manganese, with carbon of fairly constant but small percentages; and also the material known as "Resista," that is, the iron alloy containing about 5 per cent. of manganese and 15 to 25 per cent. of nickel. We resolved, therefore, to extend the cooling experiments to such a series of manganese alloys and for purposes of comparison to include a series of nickel-iron alloys (these also having a low and fairly constant carbon percentage). The analyses of the various sets of alloys investigated and prepared by one of the authors are shown in Table I.

6. As regards the nickel-iron alloys, if an accurate quantitative investigation had been the aim of the research, it would have been better, of course, to work with binary alloys as pure as possible, but for a general survey this material seemed sufficiently promising. The specimens were prepared in duplicate at the Research Laboratory of the Hadfield Works, at Sheffield, one set being retained for immersion in liquid air there, and the other sent to the Cryogenic Laboratory at Leiden for immersion in liquid hydrogen. In the preparation of the specimens and in the experimental work at Hecla Works the authors have been assisted by the following Members of the Research Staff at the works mentioned, namely, Messrs. S. A. Main, B.Sc., T. G. Elliot, F.I.C. and W. J. Todd, to whom the authors tender their best thanks for the assistance rendered in these researches, which have required much time and patience to carry out. The size of the specimens was about

Table I.

Mark.	Analysis.			
	C.	Si.	Mn.	Ni.
Manganese-Iron Alloys.				
2423	Less than 0·1 per cent.	—	1·10	
1379 B/2	0·08	—	3·50	
2425	Less than 0·1 per cent.	—	4·10	
2426	Less than 0·1 per cent.	—	5·50	
1379 C/1	0·12	—	6·67	
2427	Less than 0·1 per cent.	—	10·50	
3156/2	0·14	—	11·41	
2428	Less than 0·1 per cent.	—	12·90	
2429	Less than 0·1 per cent.	—	15·70	
2430	Less than 0·1 per cent.	—	19·80	
1379 F	0·07	0·13	22·84	
Manganese 5 per cent., Nickel 15 per cent.				
1109 D	0·60	0·84	5·04	14·55
Manganese 6 per cent., Nickel 25 per cent.				
1414 B	1·18	Est., 0·56	6·05	24·30
Nickel-Iron Alloys.				
1287 A	0·19	0·31	0·79	0·27
B	0·14	0·20	0·70	0·51
C	0·13	0·23	0·72	0·95
D	0·14	0·21	0·72	1·88
E	0·19	0·20	0·65	3·73
F	0·18	0·31	0·65	5·89
G	0·17	0·28	0·68	7·78
H	0·16	0·20	0·86	9·43
H/1	0·24	—	0·68	10·65
I	0·18	0·22	0·93	11·24
J	0·23	0·24	0·93	15·63
K	0·19	0·27	0·93	19·80
L	0·16	0·30	1·00	24·67
M	0·14	0·38	0·86	29·39
N	0·14	0·28	1·49	43·00

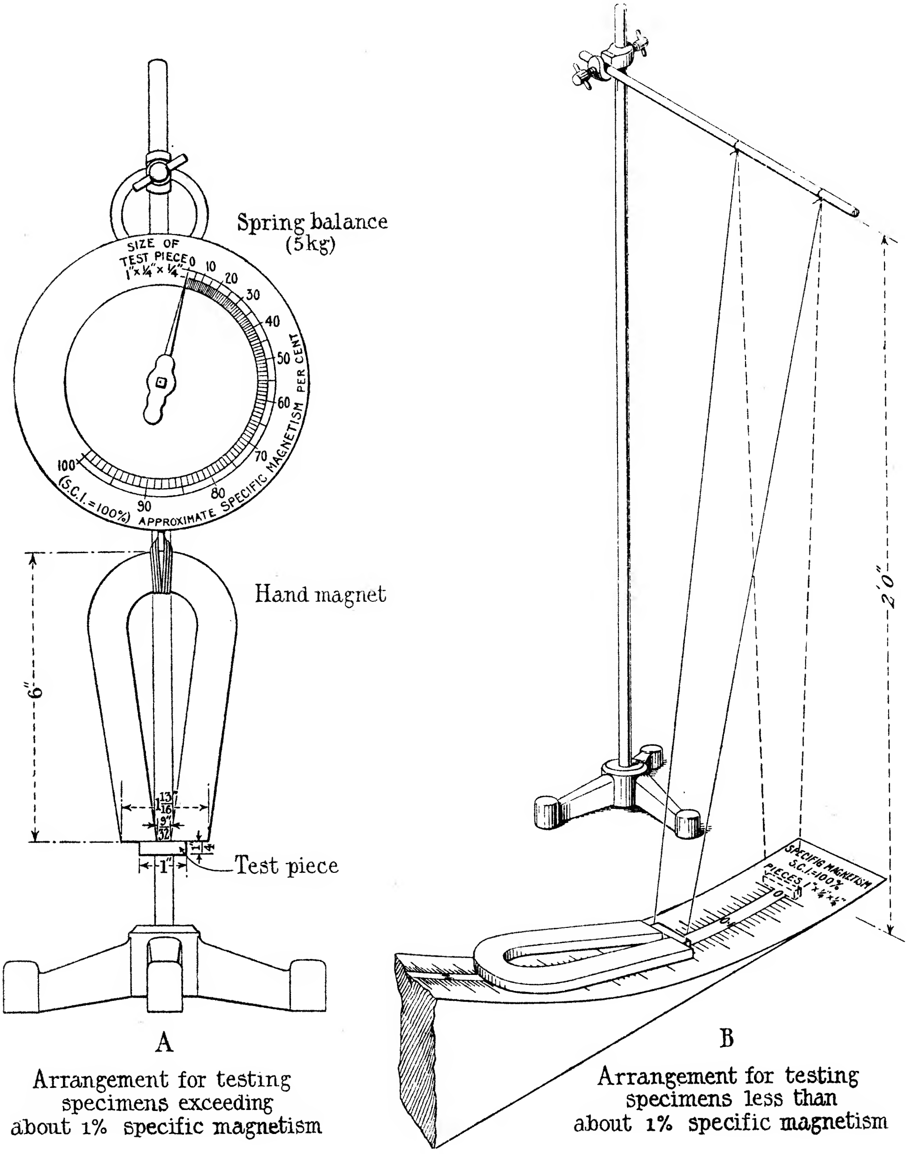
0·7 cm. square × 2·75 cm., and they were quenched from 1000° C. in water at atmospheric temperature.

SECTION 2.—*Method of Investigation.*

1. For the reason mentioned in Section 1, no complete magnetisation curves were recorded, nor was the saturation magnetisation measured by an accurate method as carried out by Hegg for pure iron-nickel alloys, but in the present case it was considered sufficient to measure the attraction in a non-homogeneous field by a simple method.

2. At the Hecla Works Laboratory the specimens were tested magnetically before and after immersion in liquid air, by the attractive force of a 6-inch

hand magnet placed with both poles in contact with the specimens, the force being measured either by a spring balance for the more magnetic, or by gravity for the less magnetic specimens (*i.e.*, less than about 1 per cent. specific magnetism, fig. 1). This method while necessarily approximate, has been found to give results agreeing fairly closely with those obtained from saturation tests by the Isthmus method. Tests on the actual Leiden



A

Arrangement for testing specimens exceeding about 1% specific magnetism

B

Arrangement for testing specimens less than about 1% specific magnetism

Fig. 1.

specimens by this method also agreed closely with the results obtained at Leiden, except for a tendency to give rather lower values for the less magnetic specimens. The Brinell hardness was also measured before and after immersion.

3. As regards the measurements carried out at Leiden, it was desirable for a reason explained later (Section 5) to execute the measurements not only before and after the immersion in liquid hydrogen and helium, but also *during* the immersion. In order to determine the attractional forces on the different samples quickly, without losing too much hydrogen, it was necessary to construct a special apparatus, as it necessitates the removal of the specimen from the bath of liquid hydrogen, and its replacement by another, without opening the cryostat too much, or letting the air enter. We succeeded in realising these conditions by the following apparatus.

SECTION 3.—*Apparatus.*

1. Figs. 2 and 3 show the apparatus, which might be termed a kind of balance, the beam being rectangular in form. By placing the weights on the scale, S, the force which the field exerts on the magnetised bar in the box, B, is determined. The vacuum glass being filled with liquid hydrogen the experiment was carried out in the following manner:—The vacuum glass with cap was moved down along the glass tube, G, until the pointer, P, reached a scratch previously made on the glass. By now raising the box, B, from the shuttle, Sh, by turning the handle, H, which works on an eccentric, E, it comes just between the apertures C_1 and C_2; the tested bar can be pushed by means of a specially made rod from the box B through one of the apertures C, and replaced by another, as in fig. 4 (the new specimen is introduced from the right; immediately on the removal of the tested specimen, the cover D is screwed on).

2. The vacuum glass is then moved along the glass tube G until the pointer marks its original position. The rubber ring, R, usually closes sufficiently tight to prevent movement of the vacuum glass, and, moreover, the point of P rests in a small hole. Any movement of the glass is thus entirely prevented. All parts of the balance were made from non-magnetic material, except the steel pins on which the apparatus hangs. One of these pins rests in a hole, the other in a slot. When the balance is placed in the magnetic field, it is mounted on a cross-sledge for easy adjustment. When not in use, or when the vacuum glass is to be filled with liquid hydrogen, or when a new sample is to be inserted, the beam is removed from between the poles and placed on an auxiliary table, to spare the pins and to have more room for operating. The vapour rising from the liquid hydrogen boiling in G must have a vent in

order to obtain a quiet boiling; for this purpose the outlet at the top of G and the outlet of the vacuum glass are connected, by means of a rubber tube, to a T-shaped glass tube, through which the escaping vapours may be conducted, if necessary, to the gas-holder. When the measurements are to be made and the balance must be free, the T-piece is naturally disconnected from the gas-holder. The electromagnet was the great Weiss electromagnet of the Laboratory.

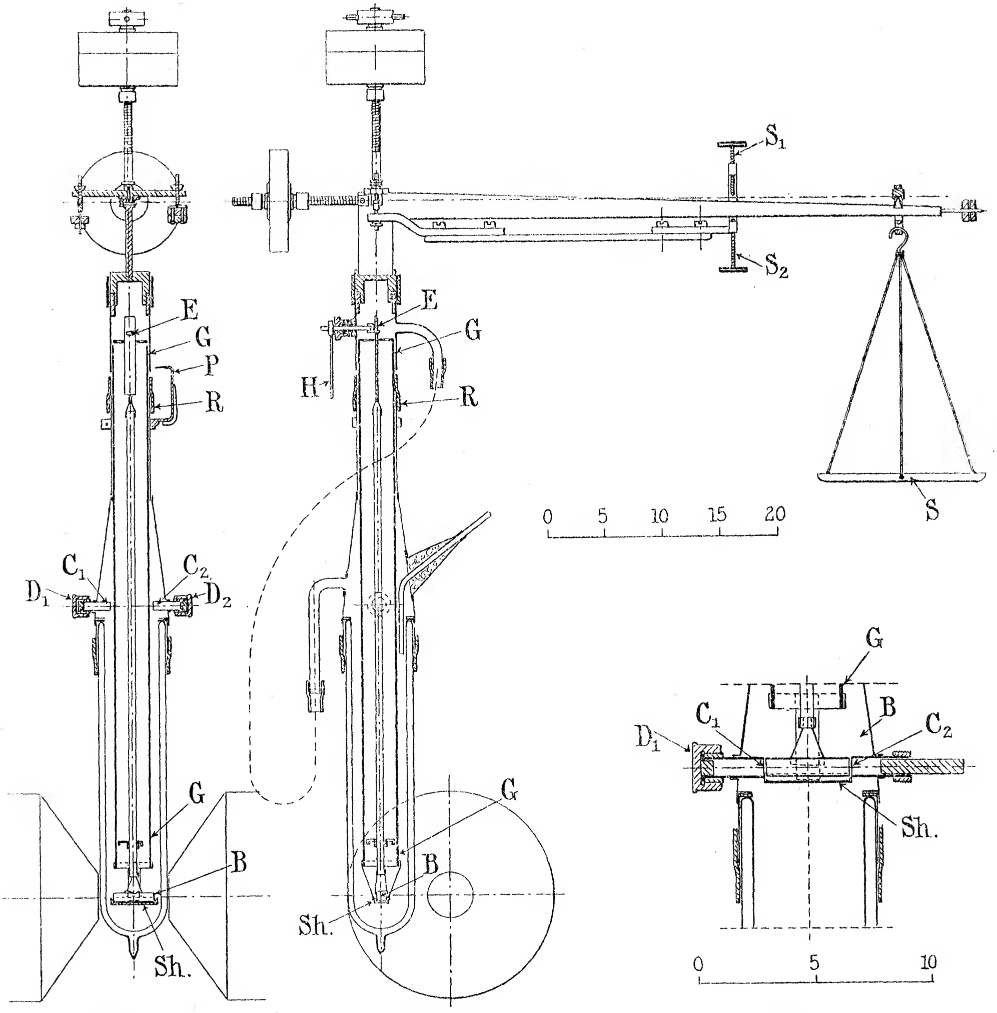


Fig. 2. **Fig. 3.** **Fig. 4.**

SECTION 4.—*Measurements.*

To execute the measurements, the cross-sledge with the bearings of the beam was arranged so as to make the edge of the balance parallel to the (horizontal) axis of the magnet and thus cut perpendicularly in the middle by the plane of symmetry passing between the poles. The steel pins being adjustable, it could be so arranged that the middle of the box, B, moved in this plane of symmetry, the bar contained in the box being always perpendicular to the plane. The counterweights on the beam were brought into position to cause the lever arm on which the scale S worked to be horizontal when the balance was at rest. The lower of the two screws S_1 and S_2, was raised until it only just touched the beam, the upper one was lowered to a few tenths of a millimetre above the beam, in order to prevent large oscillations.

2. The centre of the sample under investigation was in all cases at the same distance from the axis of the field, about 6 cm. The current through the electromagnet was then switched on and raised to 5 ampères. The field intensity in the centre (distance between the poles = 61 mm.) is about 4000 Gauss, the intensity of the external field in the centre of the bar about 2400, and the fall of intensity ($d\mathrm{H}/dx$) about 280 C.G.S. The attraction exerted on the bar turned the beam to touch the screw S_1; by putting the weights in the scale it was made to rest on S_2. The weight required to bring the beam just into contact with S_2 was thus determined. The distance between the beam and S_1 being very small, this weight differed only very slightly from that needed to remove it from S_1.

3. A weight of P grammes in the scale corresponded with an attraction on the bar of 0·766 P grammes. P varied for the different samples from about 800 to 1 grm. and could be determined easily with an accuracy of 0·1 grm. The attraction exerted on the apparatus without the sample was quite negligible. P was determined for both directions of the current through the electromagnet, but the difference was always very slight: the effect of hysteresis of the samples was not appreciable.

4. For purposes of comparison, the attraction exerted on a sample of material known as Swedish charcoal iron (S.C.I.) of the same size as the other samples was also measured. For this measurement at the Hecla Works this very pure iron was used. A specially selected batch of about 2 tons of the material has been used by one of us in all his experiments during the last twenty-five years, and may be taken as characteristic of and representing the physical and other qualities of pure iron. We refer to it as "S.C.I." The following is its percentage analysis:—

	C.	Si.	S.	P.	Mn.	Fe (by diff.).	Total impurities.
"S.C.I." ...	0·045	0·07	0·005	0·004	tr.	99·876	0·124

5. The results obtained at Leiden originally referred to a rather less pure

iron, designated "L." The experiments at Leiden having been finished, a sample of it was analysed at the Hecla Works. It has the following composition:—

	C.	Si.	S.	P.	Mn.	Cr.	Fe (by diff.).	Total impurities.
"L" ...	0·05	0·03	0·013	0·068	Nil	0·09	99·749	0·251

6. Under the field-conditions indicated above, it was attracted 1 per cent. less than the pure iron from the Hecla Works. The original numbers obtained, therefore, which had reference to the "L" material, have been lowered by 1 per cent.

SECTION 5.—*Results and Discussion.*

1. *General Remarks.*—The results of immersion in liquid air at Hecla Works are shown in Table II and figs. 5 and 6; those of immersion in liquid hydrogen at Leiden in Table III and figs. 7 and 8. Beyond noting that the results at Hecla Works are in agreement in a satisfactory way with the results from liquid hydrogen at Leiden, it is not necessary to refer individually to them as regards the magnetism of the specimens. The irreversible ranges indicated both for the nickel and manganese steels also compare well with those shown in the Leiden experiments. As regards the Brinell hardness, the irreversible change both in the iron-nickel alloys and in the limited intermediate range of iron-manganese alloys is accompanied by a distinct increase in hardness. Where there is no marked change in the specific magnetism the hardness also does not show any marked change.

2. *Theory of Low Critical Points for the Manganese-Iron Alloys.*—The experiments show that the *non-magnetic manganese alloys do not become magnetic either by immersion in liquid air or by immersion in liquid hydrogen; neither are they magnetic at the temperature of liquid hydrogen itself.* (Here and in the following discussion the importance of the measurements made at the temperature of liquid hydrogen appears.) The 11·4 and 12·9 per cent. manganese alloys may be in two different magnetic conditions at atmospheric temperature; the latter, moreover, is remarkable in being more strongly magnetic after immersion than during immersion in liquid hydrogen. Apparently for these alloys atmospheric temperature lies between the two critical temperatures, liquid air temperature being below the lower critical point.

2. If the non-magnetic condition of the higher manganese-iron alloys is to be explained by one or both of their critical temperatures being exceedingly low, there are two possibilities:—

(*a*) Atmospheric temperature is between the two critical temperatures.

(*b*) Atmospheric temperature is higher than the upper critical temperature.

Table II.—Effect of Immersion in Liquid Air (−182° C.) at Hecla Works.

Specimens previously quenched in water from 1000° C.
The specific magnetism figures have reference to Swedish charcoal iron taken as 100.
The specimens were immersed in liquid air for 12 minutes.

Mark.		Before immersion in liquid air.		After immersion in liquid air.	
		Specific magnetism.	Brinell* hardness.	Specific magnetism.	Brinell* magnetism.
	Low Carbon Manganese-Iron Alloys.				
	per cent. Mn.				
2423	1·10	96	166	95	142
1379 B/2	3·50	92	370	91	394
2425	4·10	90	370	90	370
2426	5·50	89	370	90	370
1379 C/1	6·67	86	288	82	280
2427	10·50	50	394	60	430
3156/2	11·41	35	370	53	436
2428	12·90	8	274	20	318
2429	15·70	1	190	1	210
3430	19·80	0·42	199	0·42	214
1379 F	22·84	0·40	202	0·45	208
	Manganese 5 per cent., Nickel 15 per cent.				
1109 D		0·10	142	0·20	138
	Manganese 6 per cent., Nickel 25 per cent.				
1414 B		0·30	128	0·30	128
	Low Carbon Nickel-Iron Alloys.				
	per cent. Ni.				
1287 A	0·27	93	156	97	155
B	0·51	93	162	96	176
C	0·90	90	166	95	156
D	1·88	87	342	93	336
E	3·73	90	364	92	342
F	5·89	86	342	85	370
G	7·78	88	370	86	364
H	9·43	87	418	84	400
H/1	10·65	87	432	88	408
I	11·24	80	436	86	418
J	15·63	76	476	75	476
K	19·80	74	400	78	394
L	24·67	49	258	78	370
M	29·39	3	107	69	332
N	43·00	88	129	90	125

* 10 mm. ball, 1000 kgrm. load.

As regards (*a*), if the first hypothesis is true, our experiments show that the lower critical temperature must be still lower than the boiling point of liquid hydrogen. In order to test this idea, the non-magnetic manganese alloys were immersed *in liquid helium* (−269° *C.*) *for some two and a half hours, but, when they were again at atmospheric temperature, none of them*

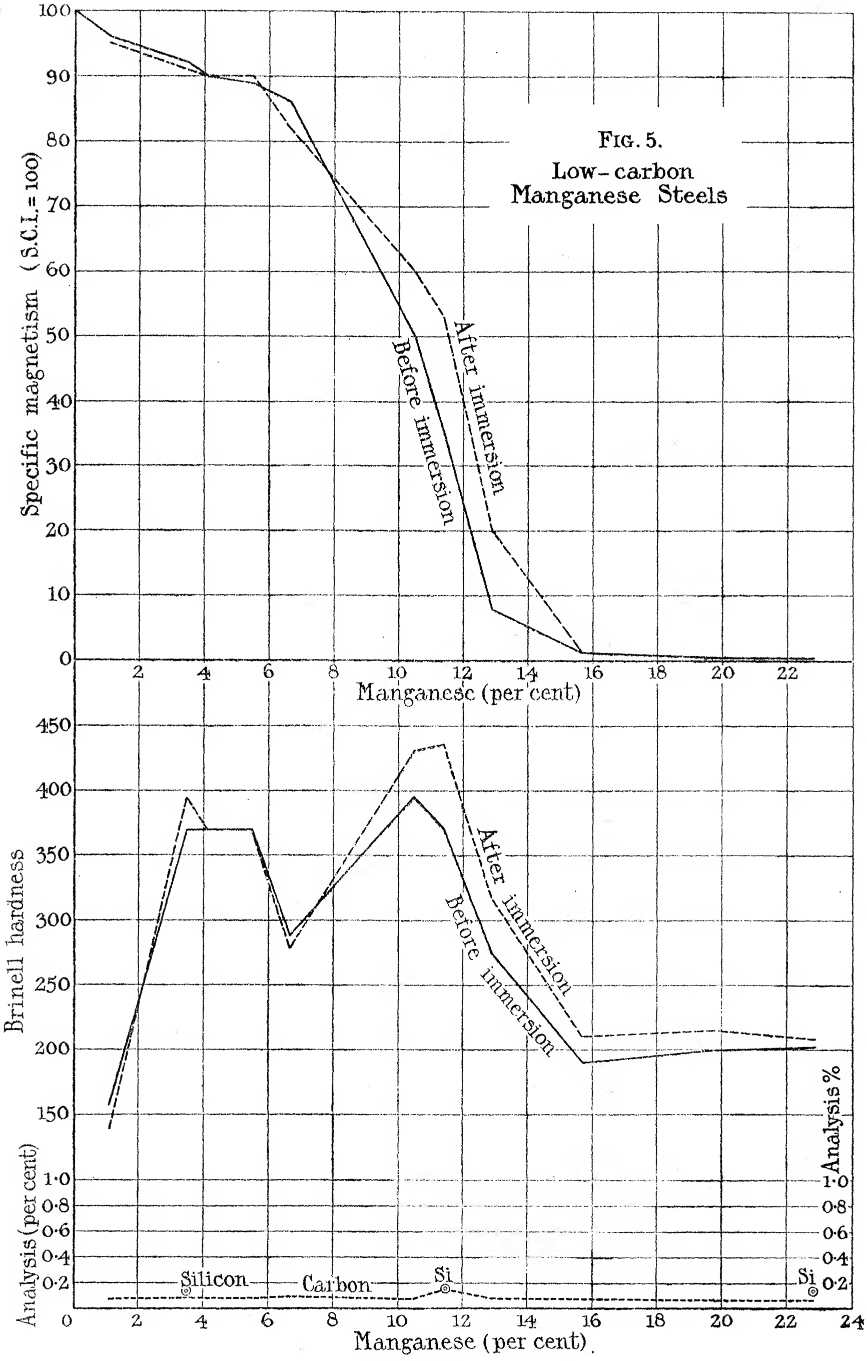


FIG. 5.
Low-carbon
Manganese Steels

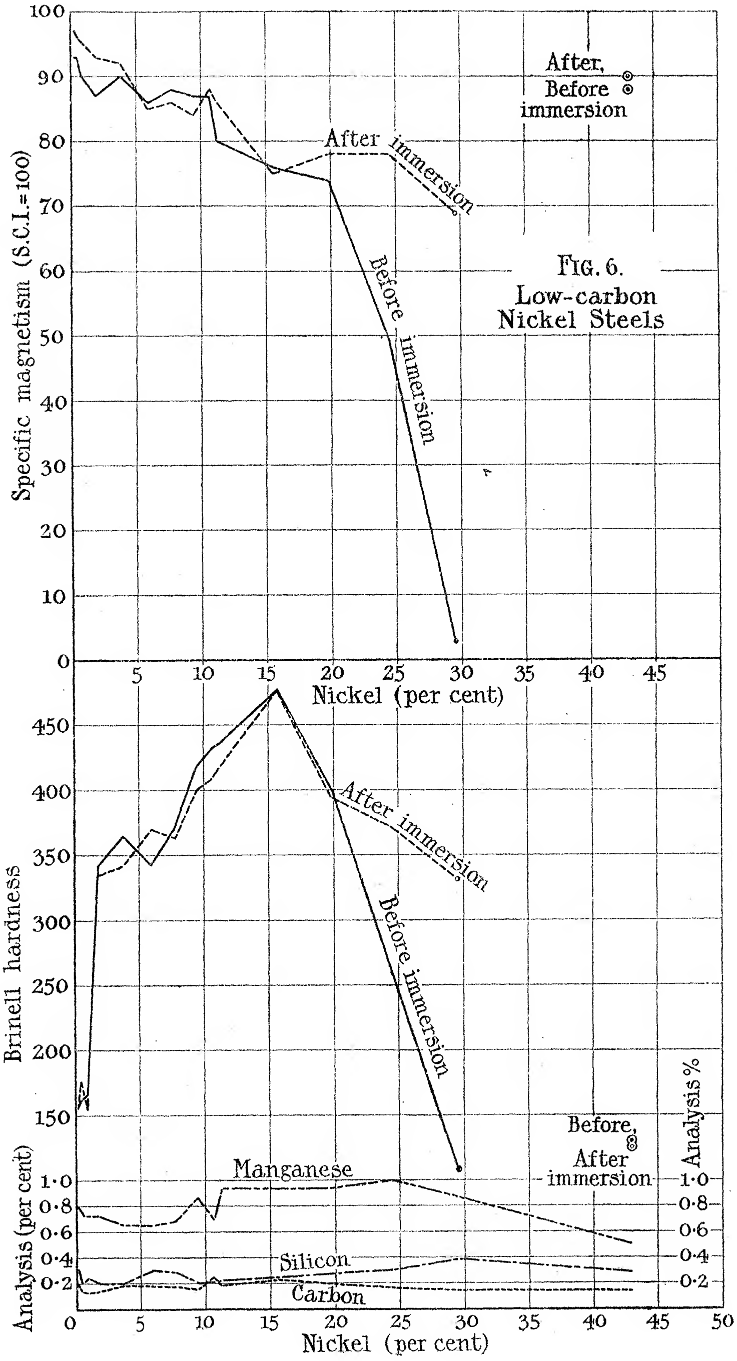


FIG. 6. Low-carbon Nickel Steels

Table III.—Effect of Immersion in Liquid Hydrogen (−253° C.) at Leiden.

Specimens previously quenched in water from 1000° C.
The specific magnetism figures have reference to Swedish charcoal iron taken as 100.

Mark.		Specific magnetism.		
		Before immersion in liquid hydrogen.	During immersion in liquid hydrogen.	After immersion in liquid hydrogen.
		Low Carbon Manganese-Iron Alloys.		
	per cent. Mn.			
2423	1·10	97·0	99·6	97·4
1379 B/2	3·50	93·0	96·4	93·5
2425	4·10	94·2	96·7	94·3
2426	5·50	92·7	95·8	92·7
1379 C/1	6·67	91·1	94·2	91·5
2427	10·50	51·9	55·4	53·8
3156/2	11·41	38·5	46·0	46·2
2428	12·90	9·8	15·7	17·7
2429	15·70	2·9	3·1	3·1
2430	19·80	0·81	0·89	0·80
1379 F	22·84	0·53	0·59	0·53
		Manganese 5 per cent., Nickel 15 per cent.		
1109 D		0·77	1·74	0·96
		Manganese 6 per cent., Nickel 25 per cent.		
1414 B		1·49	8·78	1·57
		Low Carbon Nickel-Iron Alloys.		
	per cent. Ni.			
1287 A	0·27	96·2	98·0	96·4
B	0·51	97·5	99·4	97·8
C	0·90	97·5	99·9	97·9
D	1·88	94·4	97·1	94·7
E	3·73	95·0	97·9	95·8
F	5·89	94·8	98·3	95·1
G	7·78	94·8	98·0	95·2
H	9·43	96·3	99·2	96·4
H/1	10·65	90·3	93·8	90·6
I	11·24	93·5	96·8	93·9
J	15·63	84·6	88·7	85·9
K	19·80	78·3	86·6	83·0
L	24·67	48·1	83·6	79·8
M	29·39	8·9	72·1*	64·5
N	43·00	71·0	81·0	72·0

* During a second immersion the specific magnetism was 76·2.

showed any appreciable change in magnetic condition (Table IV). The attraction during the immersion in liquid helium was not measured on account of the extraordinary difficulties connected with all work at helium temperatures. It might be asked also if it was not necessary to keep the samples even longer in the liquid helium to obtain the magnetic transformation, since all transformations occur very slowly at low temperatures. It must be remarked, however, that the magnetic transformations seem to occur rather quickly, 12 minutes in liquid air being sufficient for many transformations (see Table II). It appears, therefore, that on hypothesis (*a*) the lower critical temperature for 15, 19·8, and 22 per cent. manganese must be lower than the boiling point of liquid helium (−269° C.). As that temperature, however, for 12·9 per cent. manganese lies above the boiling point of liquid air, there would be an enormous difference between the critical temperatures of two neighbouring alloys.

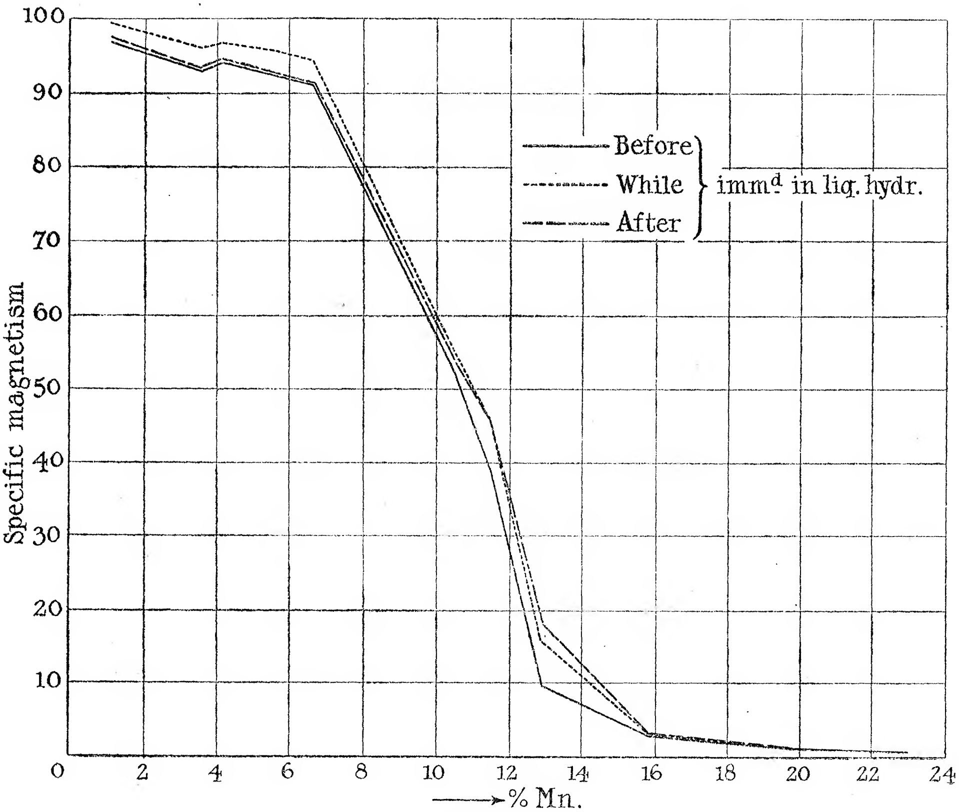


Fig. 7.—Specific magnetism iron-manganese alloys.

Regarding hypothesis (*b*), in this case we must conclude from our measurements in liquid hydrogen that the lower critical temperature must be below the boiling point of liquid hydrogen, since the alloys appear still to be non-magnetic at that temperature. The immersion in liquid helium being unaccompanied by a measurement in liquid helium itself does not in this case prove anything.

Though hypothesis (*b*) fits the results of this research quite well (see fig. 8) still it seems as little acceptable as hypothesis (*a*), if we take into account some unpublished experiments of one of us, and of the observations of

Gumlich, who determined the magnetic critical points themselves by a direct method, and whose results may be seen from fig. 9. Moreover, there appears to be an explanation, as given below, which has many advantages over the theory of the low critical points.

3. *Suggestion of two Manganese-iron Compounds.*—The form of magnetism curve for the iron-manganese alloys in figs. 5 and 7 is very suggestive. Considering only the curves representing the condition stable at low temperature, that is, after immersion in liquid air or liquid hydrogen, from zero manganese to about 7 per cent., the magnetism falls in a practically linear manner. From about 7 per cent. manganese to about 16 per cent. manganese, the fall in magnetism is again approximately linear, but at a very much more rapid rate.

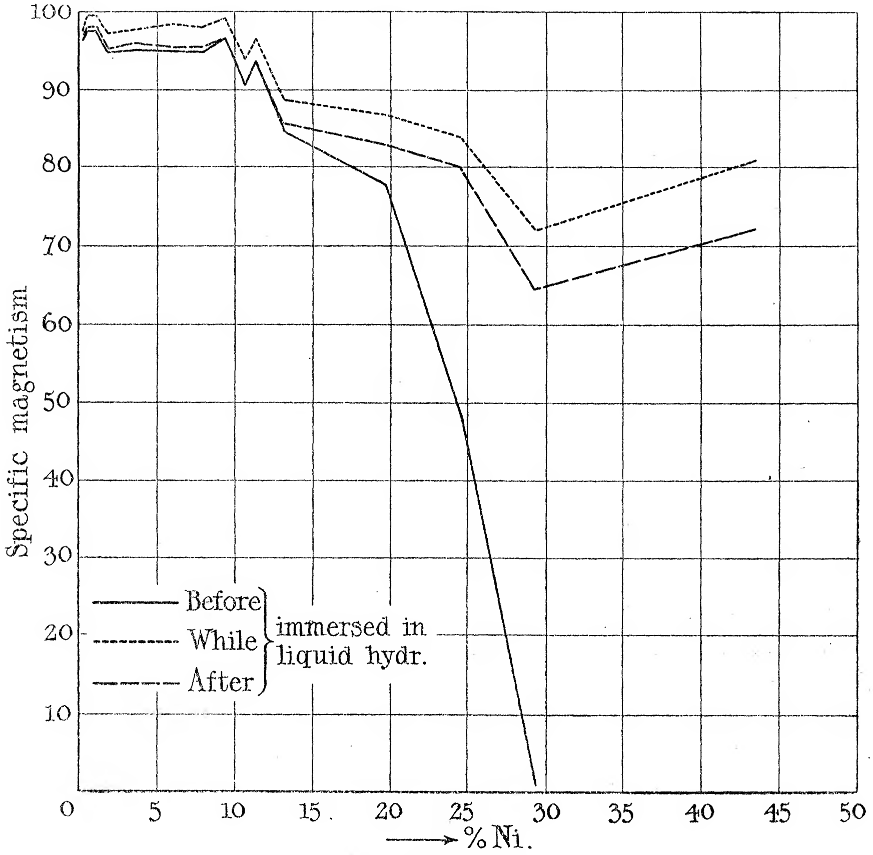


Fig. 8.—Specific magnetism iron-nickel alloys.

This strongly suggests definite chemical compounds of iron and manganese, containing respectively about 7 and 15 per cent. manganese. From this

Table IV.—Effect of Immersion in Liquid Helium (−269° C.) at Leiden.

Specimens previously quenched in water from 1000° C., except where otherwise stated.
The specific magnetism figures have reference to Swedish charcoal iron taken as 100.
The specimens were immersed for about 2½ hours.

Mark.	Composition.	Specific magnetism.	
		Before immersion.	After immersion.
	Per cent. Mn.		
2428	12·9	17·7	17·7
2429	15·7	3·3	3·3
2430	19·8	0·70	0·72
1379 F	22·8	0·50	0·50
1109 D	0·60 per cent. C; 5·0 per cent. Mn; 15 per cent. Ni	0·99	0·98
1414 B	1·18 per cent. C; 6·0 per cent. Mn; 25 per cent. Ni	1·51	1·51

Mark.	Heat treatment.	Specific magnetism.	
		Before immersion.	After immersion.
Manganese steel B ...	As forged	0·13	0·12
Manganese steel D ... 1·20 per cent. C. 12·96 per cent. Mn	500° C. for 60 hours, then re-forged and water-toughened.	0·13	0·16

point of view, the alloys containing from 0 to 7 per cent. manganese would consist of a mixture of pure iron, and the less manganiferous compound of the two; between 7 and 16 per cent. manganese there would be a mixture of the two iron-manganese alloys; and, above 16 per cent., of a mixture of the more manganiferous compound with pure manganese. From such an assumption, the compounds would have a specific magnetism of about 85 per cent., and practically zero, respectively.

The presence of such intermediate compounds might further go to explain the behaviour of the alloys as regards the presence or absence of critical points on heating and cooling. Above 16 per cent. manganese, the non-magnetic (or at most only slightly magnetic) iron-manganese compound, is mixed with the non-magnetic element manganese. Therefore no critical magnetic change points are to be expected in the range above this percentage. Approaching 16 per cent. manganese from the lower percentages, the proportion of the less manganiferous and magnetic iron-manganese alloy (about 7 per cent. manganese), admixed with the non-magnetic iron-manganese alloy (about 16 per cent. manganese), becomes less and less; the main proportion of the material consists of the non-magnetic constituent, which has no critical points; consequently, the original magnetic change points in the material are evanescent.

A reference to the curve of Brinell hardnesses in fig. 5 shows minima of hardness at about 7 and 16 per cent., passing through maxima at points between 0 and 7 per cent. and 7 and 16 per cent. This again would be in conformity with the existence of the two compounds of iron and manganese referred to, following the usual behaviour of simple mixtures.

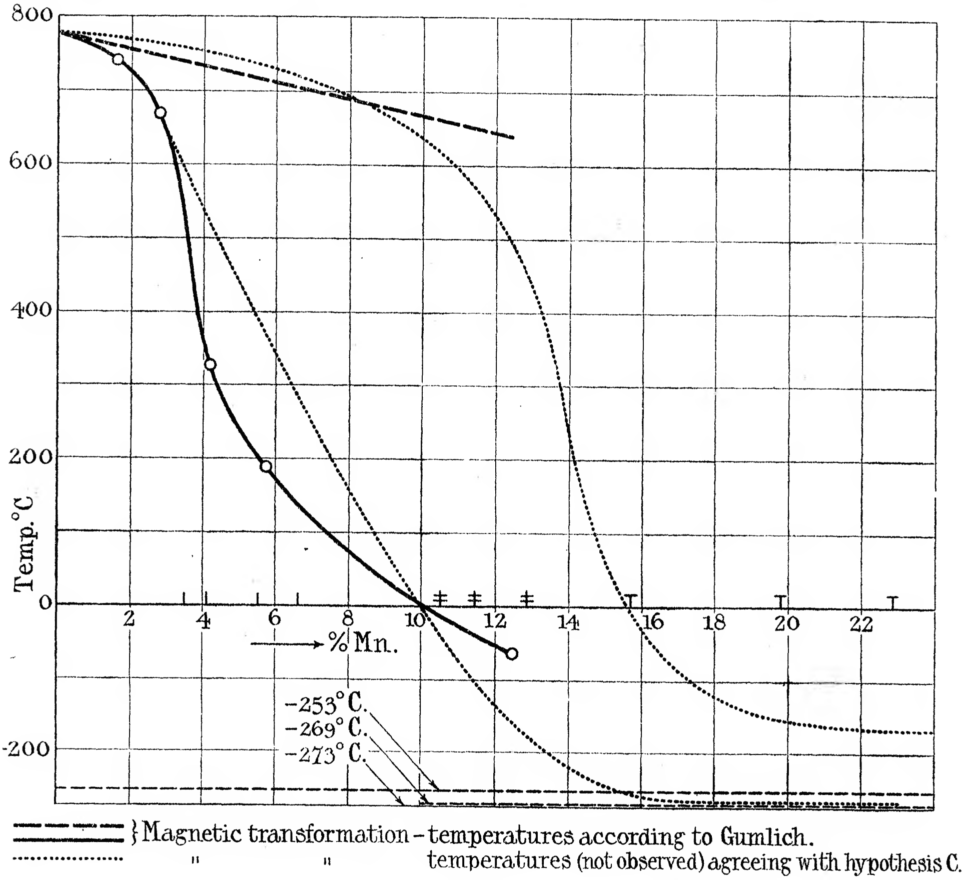


Fig. 9.

It is well known that, as a general rule, when two elements, and element and a compound, or two compounds, intermix in all proportions, the hardness of the mixture passes through a maximum as the percentage of one of the constituents is increased gradually from 0 to 100 per cent.

The data are insufficient to justify definite conclusions as to the existence of these compounds or their precise composition; the specimens are insufficient in number, especially in the critical regions, for example between 6·7 and 10·5 per cent., and, again, between 12·9 and 19·8 per cent. The curves, therefore, which have been drawn by joining up the points of observation, only roughly approximate to the complete curves.

The compound represented by Fe_5Mn would contain about 16·4 per cent. manganese; that represented by $Fe_{12}Mn$, 7·6 per cent. manganese. Fe_6Mn would contain 14·1 per cent. manganese, and would appear to be a more likely compound from the point of view of valency, but with a higher percentage than this, namely, specimen 2429, with 15·7 per cent. manganese, there is still a very small, though definite, amount of magnetism in the material.

It will be understood, therefore, that the suggestion as regards these compounds is put forward in quite a tentative manner, as likely to provide a more satisfactory alternative to the theory that the non-magnetic character of the more manganiferous iron-manganese alloys is due to the progressive lowering of the critical magnetic change point of the iron, even below the lowest temperatures practically attainable.

It is introducing no new principle to suggest that iron, by combination with another element, may entirely lose its ferro-magnetic character. On the other hand, the tendency to associate the magnetic character simply with changes of micrographic structure connected with the critical points disregards any physical differences which there may be between materials having similar micrographic structure.

It may be added that our results agree in many respects with those of Gumlich, who found for the saturation magnetism of manganese-iron alloys, after quenching from 800° C., two straight lines. The saturation magnetism in iron decreases with increasing percentages of manganese, linearly at first, that is up to about 7·5 per cent. manganese, slowly then from 7·5 per cent., rapidly down to zero at 15 per cent. manganese. Gumlich finds, however, that the decrease of magnetism up to about 8 per cent. manganese is proportional to the percentage, and that the manganese acts as a diluent only in these alloys. As regards the higher alloys, he mentions also the suggestion by Hilpert of a non-ferromagnetic compound, between iron and manganese, but his theory seems to differ from that just given. Gumlich observed discontinuities also in the densities and in the electrical resistance, though not all exactly at the same percentages of manganese.

Micrographical examination does not give any indication of a special constituent at the critical percentages indicated by the physical properties. This, however, is consistent with the compounds having a similar crystalline character to the component elements, iron and manganese. Such cases occur with some other elements which form compounds.

The abrupt bend in the curves at 7 per cent. manganese must indicate something special for this composition, as its critical temperatures are well above atmospheric temperature, and this abrupt change cannot be accounted for by the same explanation as applies in the case of nickel-iron alloys.

As regards the composition of such compounds, supposing they exist, while the compounds already established in the case of other metals usually have a simple atomic proportion, there do exist several compounds in which one of the elements greatly predominates. Examples of these are given by one of the latest authorities (Giua), so that the compounds of iron and manganese suggested would not be unique in this respect. The same authority also points out that the formulæ for inter-metallic compounds are not necessarily determined by the ordinary valencies of the separate elements, so that *prima facie* there is nothing to preclude even compounds of the type Fe_5Mn, though, as mentioned, nothing really definite is suggested as to the composition of these compounds. If the suggestion lead investigators to study the matter further, or if it lead to a more satisfactory theory, it would appear to be fully justified.

4. *Effect of Carbon.*—In view of the important effect of carbon in manganese steel, it was thought possible that the presence of even 0·10 per cent. of carbon in the iron-manganese alloys forming the subject of this research might have an appreciable influence on the results obtained. It has been previously shown by one of us that by annealing manganese steel at about 500° C. for several hours the carbon is deposited as a carbide, forming an acicular structure.

Arnold has also isolated the carbides from annealed manganese steel, and where the manganese percentage is about 12 per cent. he finds the analysis of these carbides to correspond to the form $3Fe_3C.Mn_3C$. There is a probability that in manganese steel containing about 15 per cent. of manganese or over the double carbide has the formula $2Fe_3C.Mn_3C$. In either case, 0·10 per cent. of carbon corresponds to over 1 per cent. of the double carbide.

This method of precipitating the carbon as carbides suggested a means of rendering the alloys more pure, at any rate in respect of carbon; the carbide having been precipitated (fig. 10) leaves a matrix much freer from carbon. As, further, the carbides separated chemically from alloys containing above 10 per cent. manganese were found to be non-magnetic, their presence would not interfere with the magnetic measurements except to act as a diluent to the relative amount by which they were present. Subject to this slight dilution therefore, the magnetic qualities, after this treatment, of the alloys above about 10 per cent. manganese represent the qualities of fairly pure iron-manganese alloys. The question, therefore, as to what extent the

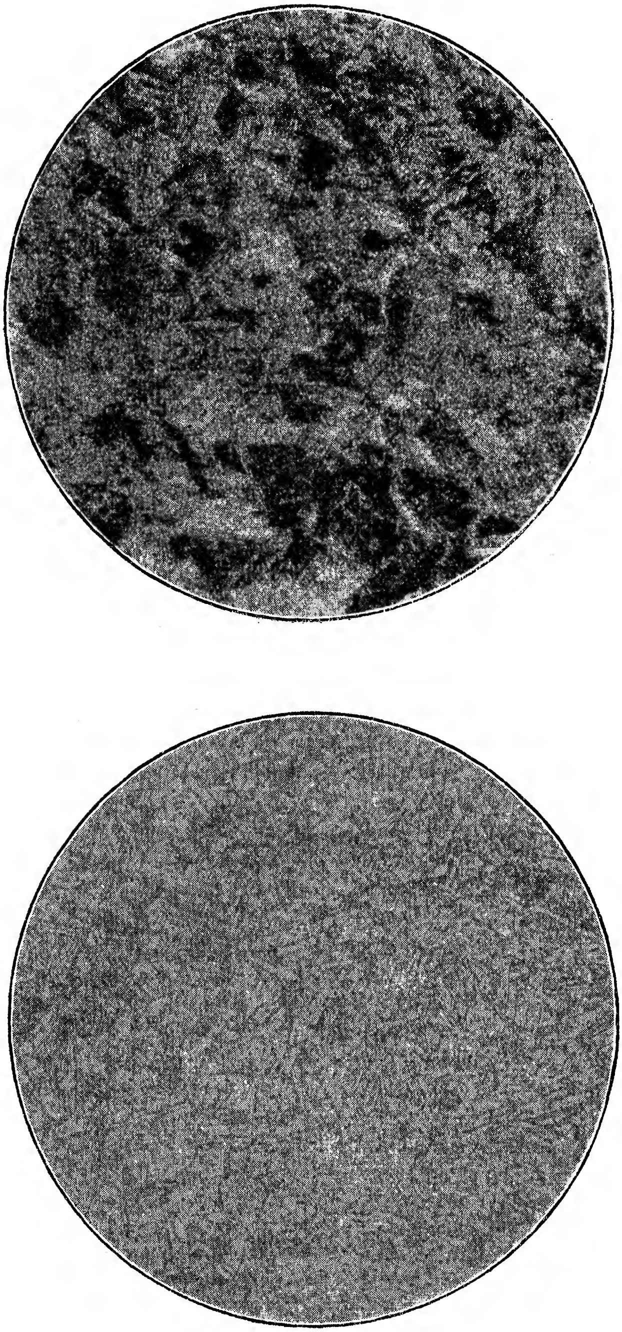


Fig. 10. ×600

irreversible range noticed in the iron-manganese alloys is influenced by, or due to, the amount of carbon present could be further investigated.

No inferences can be drawn, however, as to their magnetic qualities below about 10 per cent. manganese, as the deposited carbides are in these cases more or less magnetic, and mask the qualities of the matrix. The hardness over the whole range of the alloys is considerably influenced by the reinforcement of these hard carbides, so that also no deductions can be made as to the variation of the hardness of the matrix with variation in manganese percentage. Hardness and magnetic tests were, however, made on the whole series as a matter of interest.

Specimens $\frac{5}{8}''$ × $\frac{3}{8}''$ × $2\frac{3}{4}''$ which had previously been quenched in water from 1000° C. were heated to 500° C. for sixty hours and cooled slowly. Magnetic and Brinell hardness tests were then made at atmospheric temperature, and the specimens immersed in liquid air for twelve minutes, the tests being repeated on return to atmospheric temperature.

The results are shown in Table V and fig. 11. The important result is now obtained that only three of the specimens now show a higher specific magnetism after immersion than before.

Table V.—Effect on Immersion in Liquid Air (−182° C.) on Specimens quenched from 1000° C. in water, then re-heated to 500° C. for 60 hours and cooled slowly.

The specific magnetism figures have reference to Swedish charcoal iron taken as 100.
Size of specimens: $\frac{5}{8}''$ × $\frac{3}{8}''$ × $2\frac{3}{4}''$.
The specimens were immersed in liquid air for 12 minutes.

Mark.	Manganese (per cent.).	Before immersion in liquid air.		After immersion in liquid air.	
		Specific magnetism.	Brinell* hardness.	Specific magnetism.	Brinell* hardness.
		Low Carbon Manganese-Iron Alloys.			
2423	1·10	97	126	96	125
1379 B/2	3·50	88	268	92	263
2425	4·10	86	252	83	248
2426	5·50	86	258	86	266
1379 C/1	6·67	88	286	79	282
2427	10·50	40	350	40	364
3156/2	11·41	32	342	34	364
2428	12·90	7	286	9	306
2429	15·70	0·7	185	0·80	185
2430	19·80	0·28	231	0·20	260
1379 F	22·84	0·38	223	0·25	245

* 10 mm. ball, 1000 kgrm. load.

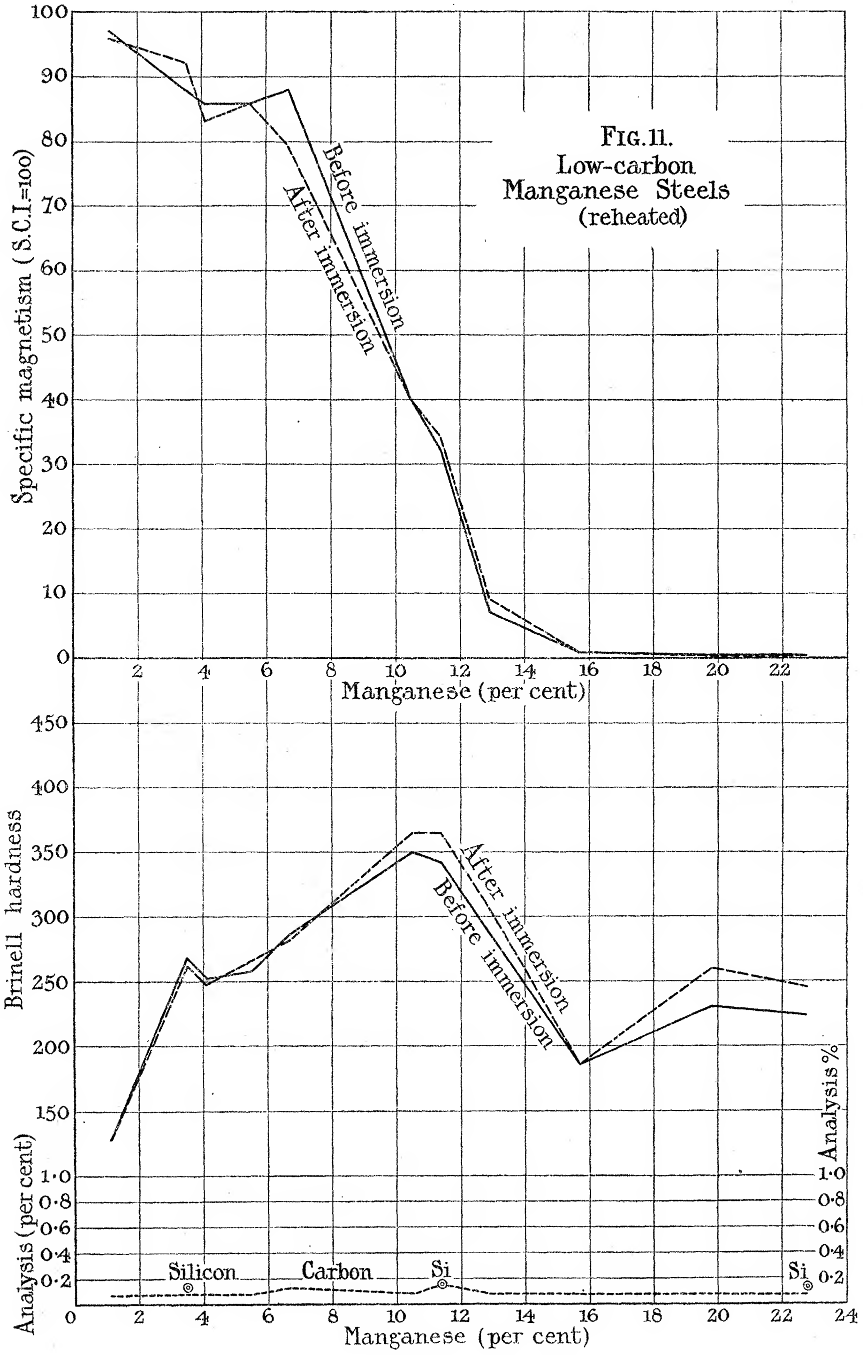


Fig. 11.
Low-carbon
Manganese Steels
(reheated)

One of these, No. 1379B/2 contains only 3·5 per cent. manganese, and is in the range affected by the presence of magnetic carbides; the other two, No. 3156/2 and 2428, are those which previously indicated an irreversible range. It will be noted that, for these, the increase of magnetism after immersion in liquid air is now very trifling. Consequently, with the elimination of carbon from the alloys, that is, leaving practically pure alloys of iron and manganese, it would appear that there is no irreversible range and that the magnetic properties at atmospheric temperature are a fairly fixed quantity for each alloy, without reference to their previous history.

As regards the Brinell hardness, as mentioned, no inferences can be drawn as to the probable relation of hardness to manganese percentage in the pure alloys; it is interesting, however, to note that the precipitation of the carbide has had the effect of making the changes due to immersion in liquid air less marked. That the minimum of hardness at about 7 per cent., noted in fig. 5, and taken as additional evidence in favour of the presence of iron manganese compounds, does not now appear, is probably due to the considerable influence of the deposited carbides in determining the Brinell number.

5. *The other Alloys.*—The *manganese-nickel steels* (known as "Resista" steels) are more strongly magnetic at hydrogen temperature than at atmospheric temperature, as generally happens in a small degree with ferro-magnetic, and in a higher degree with para-magnetic substances. Their magnetism at atmospheric temperature has not appreciably changed by immersion in liquid hydrogen nor by immersion in liquid helium, to which latter experience they were subjected, together with the pure manganese-iron alloys (Table III).

Two specimens of true manganese steel, *i.e.*, the ternary compound differing in its content of 1·25 per cent. carbon from the alloy 2428 included in the series of manganese-iron alloys (Table III) in its non-magnetic condition, have been immersed also in liquid helium, but without appreciable effect on their magnetism at atmospheric temperature (Table IV).

With regard to the *iron-nickel alloys*, these show the well-known irreversibility that might be expected, and are in this respect in accordance with the work of other authors.

Summary.

1. A series of iron-manganese and iron-nickel alloys, with a range of percentages of manganese and nickel respectively, has been tested in order to investigate the influence of cooling to very low temperatures (liquid hydrogen and liquid helium) on their magnetic properties, especially to

ascertain whether the iron-manganese alloys, which are non-magnetic at atmospheric temperature, become magnetic by so doing.

2. With a view to the desirability of testing not only after, but also during immersion in liquid hydrogen, an apparatus has been constructed, which makes it possible to test the samples quickly one after another at a temperature of 20° K., with as little loss of hydrogen as possible.

3. The iron-manganese alloys, containing the higher percentages of manganese, cannot be made magnetic at atmospheric temperature by cooling to the boiling point of liquid hydrogen or liquid helium.

4. The existence of one magnetic and one non-magnetic, or at most slightly magnetic, manganese-iron compound is shown to be probable, and the non-magnetic properties of the higher manganese-iron alloys may be explained by their means.

The Hardness of Solid Solutions.

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It is a well-known fact of metallurgy that the addition of one metal to another produces an increase of strength and hardness. In some alloys, this change of properties is accompanied by the formation of a new micro-constituent or phase, which is itself harder, and also, as a rule, more brittle than either of the constituent metals. In a very large and important group of alloys, however, the addition of the second metal, up to certain limits of concentration, does not lead to the formation of a second phase or constituent. Alloys of this type, when they have attained an equilibrium condition, consist of an aggregate of polyhedral crystals, homogeneous in composition so far as their micro-chemical behaviour indicates, and in most respects entirely similar to the constituent crystals of the pure metal, which forms the basis of the alloy. A typical example of this kind is furnished by the alloys of copper with zinc, containing up to about 30 per cent. of zinc. Alloys of this type are generally described as "solid solutions," on the ground that the state of intimate mixture which exists in the liquid (molten) solution of the two metals in one another is preserved in these alloys after solidification. In Continental language, such crystals are more frequently

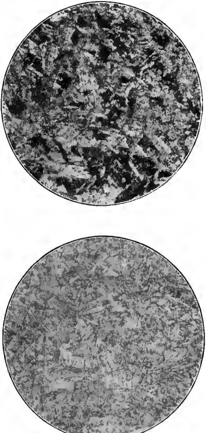

FIG. 10. ×600